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Ackermans, TMA, Francksen, NC, Casaña-Eslava, RV, Lees, C, Baltzopoulos, V, Lisboa, PJG, Hollands, MA, O'Brien, TD and Maganaris, CN (2020) Stair negotiation behaviour of older individuals: Do step dimensions matter? Journal of Biomechanics. ISSN 1873-2380

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Stair negotiation behaviour of older individuals: Do step dimensions matter?

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Article type: Original Article (Word count: 3496)

Keywords: stair negotiation; ageing; fall risk; step dimensions; multivariate stepping behaviour.

Abstract

Stair falls are a major health problem for older people. Most studies on identification of stair fall risk factors are limited to staircases set in given step dimensions. However, it remains unknown whether the conclusions drawn would still apply if the dimensions had been changed to represent more challenging or easier step dimensions encountered in domestic and public buildings. The purpose was to investigate whether the self-selected biomechanical stepping behaviours are maintained when the dimensions of a staircase are altered. Sixty-eight older adults (>65 years) negotiated a seven-step staircase set in two step dimensions (*shallow* staircase: rise 15cm, going 28cm; *steep* staircase: rise 20cm, going 25cm). Six biomechanical outcome measures indicative of stair fall risk were measured. K-means clustering profiled the overall stair-negotiating behaviour and cluster profiles were calculated. A Cramer's V measured the degree of association in membership between clusters. The cluster profiles revealed that the biomechanically risky and conservative factors that characterized the overall behaviour in the clusters did not differ for the majority of older adults between staircases for ascent and descent. A strong association of membership between the clusters on the *shallow* staircase and the *steep* staircase was found for stair ascent (Cramer's V: 0.412, $p<0.001$) and descent (Cramer's V: 0.380, $p=0.003$). The findings indicate that manipulating the demand of the task would not affect the underpinning mechanism of a potential stair fall. Therefore, for most individuals, detection of stair fall risk might not require testing using a staircase with challenging step dimensions.

Introduction

Stair negotiation is one of the most hazardous daily tasks for older adults, often resulting in falls (M. S. Roys, 2001). Indeed, falls on stairs have been identified as the leading cause of accidental death and place a substantial financial burden on the National Health Service (Scuffham, Chaplin, & Legood, 2003; Soriano, DeCherrie, & Thomas, 2007; Startzell, Owens, Mulfinger, & Cavanagh, 2000). The literature has identified tripping during the swing phase and slipping during push-off as the main underlying mechanisms for a fall during stair ascent (Templer, 1995). During stair descent, the underlying mechanisms include tripping and slipping during the loading phase, or a loss of centre of mass (CoM) control during the lowering phase (Templer, 1995).

A compromised safety on stairs has been primarily linked with deficiencies in physical capabilities, behaviour and stair design (Jacobs, 2016; M. S. Roys, 2001). In terms of stair design, staircases with a large step riser create additional demands for joint moment generation during stair ascent (Stacoff, Diezi, Luder, Stüssi, & Kramers-de Quervain, 2005) and control of the CoM during descent (Novak, Komisar, Maki, & Fernie, 2016). Staircases with a small going are thought to increase the risk for a slip during descent by reducing the available area to safely land the leading limb (M. S. Roys, 2001). Although, stair design affects safety, the majority of studies on identification of risk factors for a stair fall are limited to a staircase set in given step dimensions (Buckley, Cooper, Maganaris, & Reeves, 2013; Christina & Cavanagh, 2002; Hamel, Okita, Higginson, & Cavanagh, 2005; Mian, Narici, Minetti, & Baltzopoulos, 2007; Mian, Thom, Narici, & Baltzopoulos, 2007). Thus, it remains unknown whether the conclusions drawn regarding stair fall risk would still apply if the demand of the task had been changed by implementing more or less challenging step dimensions, within the range of step dimensions that could be encountered in various domestic and public buildings.

The few studies that have compared risk factors between staircases with different step dimensions are limited to comparisons of single biomechanical factors, such as foot positioning or dynamic balance (Johnson & Pauls, 2010; Nemire, Johnson, & Vidal, 2016; Novak et al., 2016; Riener, Rabuffetti, & Frigo, 2002; M. Roys & Wright, 2005; M. S. Roys, 2001; Wright & Roys, 2005, 2008). However, it has been shown that risky stepping strategies may be adopted at the same time with more conservative strategies (Ackermans et al., 2019). For example, older adults descending stairs have been reported to display not only a decreased clearance, which increases fall risk, but also a decreased required coefficient of friction, which indicates a more conservative strategy that could reduce fall risk (Ackermans et al., 2019). Therefore, multiple parameters, reflecting both more risky or more conservative strategies on stairs, should be used to understand the effect of different step dimensions on safety. Furthermore, the studies that compared different step dimensions used mean values, either for a single group (Riener et al., 2002; Wright & Roys, 2005), or between predetermined groups, typically, younger vs older individuals (Novak et al., 2016; Stacoff et al., 2005). This approach would not allow establishing whether a particular individual would maintain the stepping behaviour selected or would adopt a different stepping strategy when exposed to a staircase with different step dimensions. To circumvent this limitation, a recently developed multivariate approach for profiling individual stepping behaviour should be used (Ackermans et al., 2019).

The purpose of the present study was to apply a multivariate approach to investigate whether the selected biomechanical stepping behaviours of older individuals are maintained when negotiating staircases with two different step dimension configurations.

Methods

Participants

Sixty-eight older adults (age: 71.2±4.0y; body height: 1.68±0.08m; body mass: 70.2±13.4kg; males: 24) participated in the study. All participants lived independently and were recruited from the local community of Liverpool, UK. Participants were excluded if they could not negotiate both staircases in a step-over-step manner, or were using handrails or any other aid to negotiate the stairs. Written informed consent was obtained from all participants after the procedures and possible risks of the study were explained. The study was approved by the NHS research ethics committee in the UK (IRAS ID: 216671) and was conducted in accordance with the Declaration of Helsinki.

Staircase configuration

The measurements were conducted on a custom-built instrumented seven-step staircase (Ackermans et al., 2019). The kinematics were obtained using a 24 infrared camera-system (120Hz, Vicon, Oxford Metrics, UK) and kinetics were obtained through four force platforms (1080Hz, 9260AA, Kistler AG, CH) embedded in the lower four steps. The staircase was set in two different step dimension configurations. The *"shallow"* staircase was set at a rise of 15cm and going of 28cm resulting in a pitch of 28.2 degrees and the "*steep"* staircase was set at a rise of 20cm and going of 25cm resulting in a pitch of 38.7 degrees. The step dimensions of both staircases conformed to relevant building regulations in the UK (British-Standards-Institute, 1984; Department-of-the-Environment-and-The-Welsh-Office, 1992), with the *shallow* staircase representing an 'easier' public staircase and the *steep* staircase a more 'challenging' private staircase (M. S. Roys, 2001).

Procedures

Participants visited the lab on two occasions. During the first visit, they ascended and descended the *shallow* staircase at their self-selected pace in a step-over-step manner without using the handrails. Only the older adults who were confident to negotiate the *shallow* staircase in this manner were invited for the second visit, in which they ascended and descended the *steep* staircase in a similar manner. All trials were performed with the volunteers clothed in tight fitting clothes and wearing their own comfortable shoes. They were fitted in a five-point safety harness, which was attached to the overhead belay safety system. A trained member of the research team operated the belay system, ensuring that there was no tension in the rope during the measurements. To allow familiarisation, the older adults performed up to five practice trials on each staircase. Afterwards, they performed five more trials with the final three trials used for analysis. There was a break after the familiarization and the older adults tested were allowed to take as many breaks during the following trials to avoid fatigue. In all trials, the staircase was approached with the left leg, before landing on the first step with the right leg during both ascent and descent.

Data analysis

Full body kinematics were obtained using a 15 segment (head, thorax, pelvis, upper arms, lower arms, hands, thighs, shanks, feet) full-body six-degree of freedom kinematic model defined by 76 reflective markers (diameter 14 mm). The segmental data were based on Dempster's regression equations (Dempster, 1955) and used geometrical volumes to represent each segment (Hanavan, 1964). The position of the whole body CoM was estimated as the weighted sum of the various body segments using Visual3D (C-Motion, Germantown, USA). For further analysis kinetic and kinematic data were filtered using a low-pass fourth order Butterworth filter with a cut-off frequency of 6Hz. The gait events on the steps were determined using force plate data.

Kinetic and kinematic data were analysed to determine the following outcome measures, which have been described in detail previously (Ackermans et al., 2019):

1) Foot clearance. The foot clearance was calculated by projecting a virtual outline of the participant's shoe in the movement trials (Ackermans et al., 2019). The foot clearance was obtained during the swing phase when the virtual shoe outline of the leading limb passed the vertical position of the step edge up until the outline passed the horizontal position of the step edge. The minimal clearance was determined within this time frame for steps 2-6 for stair ascent and descent.

2) Proportion of foot length in contact with stair (PFLCS). PFLCS was calculated using the virtual shoe outline at touch-down on steps 2-4 for stair ascent and steps 1-4 for stair descent. The parameter was calculated using the distance of the horizontal projection of the most posterior aspect (distance x) and the most anterior aspect (distance y) of the virtual shoe outline to the step edge. The PFLCS was calculated as a percentage using the following equation: PFLCS=(distance x / (distance x + distance y))*100%.

3) Required coefficient of friction (RCOF). This parameter was calculated by dividing the resultant shear force (vector sum of the mediolateral and antero-posterior force) by the vertical force at each sample in time (Christina & Cavanagh, 2002). The peak RCOF was determined using Visual3d (C-Motion, Germantown, USA) after a threshold of 50 N for the vertical force was exceeded. For stair ascent, this parameter was calculated in late stance before push-off for steps 2-4 and for stair descent, the parameter was calculated during the loading phase in early stance for steps 1-4.

4) Cadence. Cadence was taken as the average duration of two gait cycles (one of the left limb and one of the right limb) for stair ascent and stair descent.

5) Maximal CoM angular acceleration (only during stair descent). The angular acceleration was calculated for the angle between the CoM and centre of pressure (CoP) position of the trailing leg. The maximal angular acceleration of the CoM was obtained as the peak value during the swing phase for steps 1-4 only for stair descent.

6) In addition to the five parameters listed (1-5), *the trial-to-trial variances of these parameters* were also calculated as the average of the variance across the three trials for each of the analysed steps. Variance in itself is a risk factor for falls, as more variance can indicate a person's inability to maintain a steady/safe movement pattern (Hausdorff, Rios, & Edelberg, 2001).

Statistics

To examine differences in biomechanical stepping strategies between staircases a multivariate method was applied for stair ascent and descent (Ackermans et al., 2019). The multivariate method profiled the individual stepping strategies of older adults based on the mean values of outcome measures (1-6) using k-means clustering. The optimal number of clusters was determined through a Separation – Concordance (SeCo) map (Casana-Eslava, Jarman, Lisboa,

& Martin-Guerrero, 2017; Chambers, Jarman, Etchells, & Lisboa, 2013; Lisboa, Etchells, Jarman, & Chambers, 2013). The SeCo map details the stability and separation of the solutions found for the dataset and the specified values of K. Producing a plot of the SeCo map of the proportion of solutions with a given consistency allows the user to gauge the relative performance of the solutions for a value of K, in the present study between 2-10. The optimal number of K was decided based on the guidelines that this solution is stable (concordance of close to 1) together with adequate separation (Lisboa et al., 2013). To examine differences in cluster composition, the cluster profiles (CP=$Mean_{cluster} - Mean_{overall}$)/$SD_{overall}$) were calculated for all outcome measures with a threshold subjectively set at 0.5 after examining the data. In order to measure the degree of association between clusters obtained on the *shallow* staircase and clusters obtained on the *steep* staircase, a Cramer's V index was calculated (with a value of greater than 0.35 indicating a strong association (Akoglu, 2018)) and cross-tabulations were obtained for stair ascent and descent (Cramér, 2016). Statistical analyses were performed using SPSS (version 24, SPSS Inc., California, USA) and Matlab (R2018a, Mathworks, Natick, USA). The significance level was set at α=0.05.

Results

Number of clusters

The SeCo map revealed that during stair ascent the optimal number of clusters for both staircases was three (Figure 1A, C). For stair descent the SeCo map revealed that the optimal number of clusters for the *shallow* staircase was three and for the *steep* staircase was four (Figure 1B, D).

Cluster profiles in stair ascent

For the *shallow* staircase during ascent, the CP revealed that cluster 1 differed from the overall mean by showing higher PFLCS (CP=0.61) (Table 1). Cluster 2 differed from the overall mean by showing higher foot clearance (CP=0.53), more variance in PFLCS (CP = 1.53), higher RCOF (CP = 0.84), more variance in RCOF (CP=0.81) and more variance in cadence (CP=1.48) (Table 1). Cluster 3 differed from the overall mean by showing lower foot clearance (CP=-0.62), less PFLCS (CP=-1.19) and higher cadence (CP=0.67) (Table 1).

For the *steep* staircase during ascent, cluster 1 differed from the overall mean by showing less PFLCS (CP=-0.67), more RCOF (CP=0.54) and higher cadence (CP=0.74) (Table 1). Cluster 2 differed from the overall mean by showing higher PFLCS (CP=0.66) and lower cadence (CP=-0.59) (Table 1). Cluster 3 differed from the overall mean by showing more variance in foot clearance (CP=1.42), less PFLCS (CP=-0.64), more variance in PFLCS (CP=0.62), more variance in RCOF (CP=1.07) and more variance in cadence (CP=1.65) (Table 1).

Cluster profiles in stair descent

The CP of the *shallow* staircase during descent revealed that cluster 1 differed from the overall mean by showing higher foot clearance (CP=0.56), less CoM angular acceleration (CP = -0.63), less variance in CoM angular acceleration (CP=-0.64), more RCOF (CP = 1.26), more variance in RCOF (CP = 1.20) and lower cadence (CP=-1.14) (Table 2). Cluster 2 differed from the overall mean by showing less RCOF (CP=-0.56) (Table 2). Cluster 3 differed from the overall mean by showing higher CoM angular acceleration (CP=0.95), more variance in CoM angular acceleration (CP=0.98) and higher cadence (CP=0.50) (Table 2).

For the *steep* staircase during descent, the CP revealed that cluster 1 differed from the overall mean by showing less foot clearance (CP=-0.77) and less variance in RCOF (CP=-0.51) (Table 2). Cluster 2 differed from the overall mean by showing higher CoM angular acceleration (CP=1.20) and more variance in CoM angular acceleration (CP=1.35) (Table 2). Cluster 3 differed from the overall mean by showing a higher foot clearance (CP=0.80), less CoM angular acceleration (CP=-0.50), less variance in CoM angular acceleration (CP=-0.55) and lower cadence (CP=-0.73) (Table 2). Cluster 4 differed from the overall mean by showing more variance in foot clearance (CP=0.52), less PFLCS (CP=-0.61), more variance in PFLCS (CP=1.90), less RCOF (CP=-0.90), higher cadence (CP=1.03) and more variance in cadence (CP=1.59) (Table 2).

Cluster association

For stair ascent, the Cramer's V (0.412, $p<0.001$) revealed a strong association (Akoglu, 2018) of membership of individuals clustered on the *shallow* staircase with those clustered on the *steep* staircase (Table 3). Cluster 1 for the *steep* staircase contained predominantly individuals from cluster 3 for the *shallow* staircase (56.5%) (Table 3). Cluster 2 for the *steep* staircase contained predominantly individuals from cluster 1 for the *shallow* staircase (82.4%) (Table 3). Similar to cluster 1, cluster 3 contained predominantly individuals from cluster 3 for the *shallow* staircase (45.5%) (Table 3).

For stair descent, the Cramer's V (0.380, p=0.003) revealed a strong association (Akoglu, 2018) of membership of the individuals clustered for the *shallow* staircase with those clustered for the *steep* staircase (Table 4). Cluster 1 for the *steep* staircase contained predominantly individuals from cluster 2 for the *shallow* staircase (63.2%) (Table 4). Cluster 2 for the *steep* staircase contained predominantly individuals from cluster 3 for the *shallow* staircase (52.9%) (Table 4). Cluster 3 for the *steep* staircase contained predominantly individuals from cluster 1 for the *shallow* staircase (45.8%) (Table 4). Similar to cluster 2, cluster 4 contained predominantly individuals from cluster 3 for the *shallow* staircase (62.5%) (Table 4).

Discussion

In the present study, we used a multivariate approach to characterise the stair negotiation behaviour of older adults on two staircases with steps of different dimensions. For stair ascent, three clusters were identified for both staircases. For stair descent, three clusters were identified on the *shallow* staircase and four clusters on the *steep* staircase. The clusters differed from the overall mean by 1) showing only risky strategies, 2) only conservative strategies, or 3) a combination of risky and conservative strategies. The majority of the older adults maintained their individual stair-negotiating behaviour irrespective of step dimensions.

Cluster association

A strong association of membership between clusters on the *shallow* staircase and the *steep* staircase was found for stair ascent (Cramer's V: 0.412, p<0.001) and descent (Cramer's V: 0.380, p=0.003). This indicates that the staircase with more challenging step dimensions had no effect on the clustering of the individuals tested, i.e. individuals who were clustered together on the *shallow* staircase were also clustered together on the *steep* staircase.

Stair ascent

For stair ascent, cluster 1 for the *steep* staircase consisted of 56.5% of the individuals of cluster 3 for the *shallow* staircase. Similar to cluster 3 for the *shallow* staircase, cluster 1 for the *steep* staircase displayed less PFLCS and higher cadence, which are risky strategies that could increase the risk for a slip or trip (M. S. Roys, 2001). Additionally, cluster 1 for the *steep* staircase displayed higher RCOF and did not display a reduced foot clearance. Although, the increase in RCOF indicates an additional risky strategy (Hamel, Okita, Bus, & Cavanagh, 2005), the individuals could have compensated for this by increasing their foot clearance (M. S. Roys, 2001; Templer, 1995). Furthermore, the few individuals of cluster 1 for the *steep* staircase who originated from cluster 1 and cluster 2 for the *shallow* staircase altered slightly their stepping behaviour by adopting a more risky strategy.

Cluster 2 for the *steep* staircase consisted of 82.4% of the individuals of cluster 1 for the *shallow* staircase. Similar to cluster 1 for the *shallow* staircase, cluster 2 for the *steep* staircase displayed higher PFLCS, which is a more conservative strategy (M. S. Roys, 2001). Additionally, cluster 2 for the *steep* staircase displayed a reduced cadence. Although the difference in the CP of cadence between the two staircases is small (*shallow* CP=-0.44; *steep* CP=-0.59), this could indicate that individuals used a slightly more conservative strategy when the demand increased. Furthermore, the few individuals of cluster 2 for the *steep* staircase who originated from cluster 2 and cluster 3 for the *shallow* staircase altered slightly their stepping behaviour by adopting a more conservative strategy.

Cluster 3 for the *steep* staircase consisted of 11 individuals who were spread over the three clusters for the *shallow* staircase (cluster 1: 27.3%; cluster 2: 27.3 %; cluster 3: 45.5%). The individuals displayed no conservative strategies, but risky behaviours for five out of the eight parameters, such as less PFLCS and more variance in foot clearance, PFLCS, RCOF and cadence, increasing trip and slip risk (Hamel, Okita, Bus, et al., 2005; Hausdorff et al., 2001; M. S. Roys, 2001). This indicates that the increased demand resulted in a change to a more risky stepping behaviour for the 11 individuals of cluster 3 who could not be associated to a specific cluster on the *shallow* staircase.

The findings in stair ascent indicate that the majority of the individuals of cluster 1 and cluster 2 maintained their stepping behaviour and that especially, the individuals of cluster 3 changed their stepping behaviour when the task demand increased.

Stair descent

For stair descent, cluster 1 for *steep* staircase consisted of 63.2% of the individuals of cluster 2 for *shallow* staircase. In contrast to cluster 2 for the *shallow* staircase, cluster 1 for the *steep* staircase did not display less RCOF, which is a conservative strategy (Christina & Cavanagh, 2002), but displayed less foot clearance and less variance in RCOF. The reduced foot clearance could increase trip risk and the reduced variance could indicate a more conservative strategy (Hamel, Okita, Higginson, et al., 2005; Hausdorff et al., 2001). The more challenging step dimensions resulted in small changes in the stepping strategies (indicated by the CP that ranged from 0.51-0.77) to a slightly more risky strategy. Furthermore, cluster 1 included a few individuals who originated from cluster 3 for the *shallow* staircase and slightly altered their stepping behaviour.

Cluster 2 for the *steep* staircase consisted of 52.9% of individuals of cluster 3 for the *shallow* staircase. Similar to cluster 3 for *shallow* staircase, cluster 2 for the *steep* staircase displayed higher mean and variance values in CoM angular acceleration, increasing the risk for a loss of CoM control (Buckley et al., 2013; Mian, Narici, et al., 2007). However, the individuals of cluster 2 for the *steep* staircase did not display higher cadence, which could indicate that the individuals used a slightly more conservative strategy when the demand increased. Furthermore, cluster 2 included a few individuals who originated from cluster 1 and cluster 2 for the *shallow* staircase and slightly altered their stepping behaviour.

Cluster 3 for the *steep* staircase consisted of 45.8% of the individuals of cluster 1 for the *shallow* staircase. Similar to cluster 1 for the *shallow* staircase, cluster 3 for the *steep* staircase displayed larger foot clearance, reduced cadence and lower mean and variance values for CoM angular acceleration, which are conservative strategies that could reduce trip or slip risk (Buckley et al., 2013; Hamel, Okita, Higginson, et al., 2005; Mian, Narici, et al., 2007). In contrast, cluster 3 for the *steep* staircase did not display larger average and variance values of RCOF, which could indicate that individuals used a slightly more conservative strategy when the demand increased by decreasing the risk for a slip (Christina & Cavanagh, 2002). Furthermore, cluster 3 included a few individuals who originated from cluster 2 and cluster 3 for the *shallow* staircase and slightly altered their stepping behaviour.

Cluster 4 for the *steep* staircase consisted of 8 individuals, with the majority of these individuals originating from cluster 3 for the *shallow* staircase (5/8). Cluster 4 for the *steep* staircase showed a more risky stepping behaviour compared to cluster 3 for the *shallow* staircase, by showing less PFLCS, a higher cadence and more variance in foot clearance, PFLCS and cadence, which could increase the risk for a trip or slip (Hausdorff et al., 2001; M. S. Roys, 2001). Only one of these risky behaviours was similar to the behaviours adopted by cluster 3 for the *shallow* staircase, namely a higher cadence. This could indicate that the individuals of cluster 4 for *steep* staircase who originated from cluster 2 and 3 of the *shallow* staircase altered their stepping behaviour to a more risky behaviour when the demand increased.

The findings in stair descent indicate that the majority of the individuals of cluster 1-3 maintained their stepping behaviour and that all the individuals of cluster 4 changed their stepping behaviour when the task demand increased.

Conclusion

In conclusion, older adults adopted a range of stair negotiation behaviours, including the display of solely biomechanically risky strategies, solely biomechanically conservative strategies or a mix of biomechanically risky and conservative strategies. The comparison between staircases revealed that the majority of older adults maintained their overall biomechanical stepping profile, with only slight changes in terms of risk and safety characteristics when exposed to a more challenging staircase. This indicates that most of the older adults tested were identifiable based on their stepping behaviour irrespective of the step dimensions implemented. Importantly, the present findings also indicate that the underlying mechanism of a stair fall may remain the same irrespective of step dimensions. In terms of safety, this could imply that when the stepping behaviour of an individual at risk for a stair fall is improved through targeted interventions, this individual would be safer on multiple step dimension configurations. At present, it is not possible to establish which of the behaviours for stair ascent and descent is truly safer or riskier, as it is imperative to link each cluster with a relevant metric of stair falls sustained over a follow-up period.

Acknowledgements

This work was supported by a Liverpool John Moores University studentship. We would like to express our gratitude to Denis Holzer for his help with the calculations of foot clearance and proportion of foot length in contact with stair and to the members of the RISCS (Research to Improve Stair Climbing Safety) group of Liverpool John Moores University for their help during the data collection.

Conflict of interest statement

The authors have no conflicts of interests to declare.

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Tables

Table 1.

Cluster profiles (CP) for stair ascent of the biomechanical outcome measures assessed for the two staircases. Those exceeding the threshold of ±0.5 are highlighted bold and coloured in terms of risk (red = more risky strategy; green = more conservative strategy).

	Foot clearance	Var. Foot clearance	PFLCS	Var. PFLCS	RCOF	Var. RCOF	Cadence	Var. Cadence
***Shallow* staircase**								
Cluster 1	0.19	-0.07	**0.61**	-0.29	-0.12	-0.15	-0.44	-0.31
Cluster 2	**0.53**	0.42	0.07	**1.53**	**0.84**	**0.81**	0.33	**1.48**
Cluster 3	**-0.62**	-0.07	**-1.19**	-0.20	-0.19	-0.12	**0.67**	-0.15
***Steep* staircase**								
Cluster 1	-0.05	-0.32	**-0.67**	0.17	**0.54**	-0.31	**0.74**	-0.33
Cluster 2	0.06	-0.24	**0.66**	-0.31	-0.37	-0.14	**-0.59**	-0.31
Cluster 3	-0.10	**1.42**	**-0.64**	**0.62**	0.02	**1.07**	0.28	**1.65**

Notes: *Var*: variance; *PFLCS*: proportion of foot length in contact with stair; *RCOF:* required coefficient of friction.

Table 2.

Cluster profiles (CP) for stair descent of the biomechanical outcome measures assessed for the two staircases. Those exceeding the threshold of ±0.5 are highlighted bold and coloured in terms of risk (red = more risky strategy; green = more conservative strategy).

	Foot clearance	Var. Foot clearance	PFLCS	Var. PFLCS	CoM ang. acc.	Var. CoM ang. acc.	RCOF	Var. RCOF	Cadence	Var. Cadence
***Shallow* staircase**										
Cluster 1	**0.56**	0.02	0.25	-0.05	**-0.63**	**-0.64**	**1.26**	**1.20**	**-1.14**	-0.41
Cluster 2	0.09	0.31	0.16	-0.13	-0.47	-0.49	**-0.56**	-0.35	0.13	0.18
Cluster 3	-0.43	-0.40	-0.35	0.19	**0.95**	**0.98**	-0.04	-0.26	**0.50**	0.01
***Steep* staircase**										
Cluster 1	**-0.77**	-0.43	-0.05	-0.17	-0.48	-0.31	0.02	**-0.51**	0.31	-0.23
Cluster 2	-0.07	-0.24	0.02	-0.30	**1.20**	**1.35**	0.03	0.00	0.20	0.05
Cluster 3	**0.80**	0.34	0.23	-0.29	**-0.50**	**-0.55**	0.26	0.49	**-0.73**	-0.39
Cluster 4	-0.41	**0.52**	**-0.61**	**1.90**	0.10	-0.48	**-0.90**	-0.25	**1.03**	**1.59**

Notes: *Var*: variance; *PFLCS*: proportion of foot length in contact with stair; *ang*: angular; *acc:* acceleration; *RCOF:* required coefficient of friction.

Table 3

Cross-tabulations of the clusters identified on *shallow* staircase with the clusters identified on *steep* staircase during stair ascent. A Cramer's V is calculated to measure the degree of association between the clusters.

Ascent	***Shallow* staircase**			
	Cluster 1	Cluster 2	Cluster 3	Total
***Steep* staircase**				
Cluster 1	7[a]	3	13	23
	30.4%[b]	13.0%	56.5%	100.0%
Cluster 2	28	4	2	34
	82.4%	11.8%	5.9%	100.0%
Cluster 3	3	3	5	11
	27.3%	27.3%	45.5%	100.0%
Total	38	10	20	68
	55.9%	14.7%	29.4%	100.0%
	Cramer's V = 0.412, p = <0.001			

[a] = frequency, [b] = row percentage

Table 4

Cross-tabulations of the clusters identified on *shallow* staircase with the clusters identified on *steep* staircase during stair descent. A Cramer's V is calculated to measure the degree of association between the clusters.

Descent	***Shallow* staircase**			
	Cluster 1	Cluster 2	Cluster 3	Total
***Steep* staircase**				
Cluster 1	1[a]	12	6	19
	5.3%[b]	63.2%	31.6%	100.0%
Cluster 2	2	6	9	17
	11.8%	35.3%	52.9%	100.0%
Cluster 3	11	9	4	24
	45.8%	37.5%	16.7%	100.0%
Cluster 4	0	3	5	8
	0.0%	37.5%	62.5%	100.0%
Total	14	30	24	68
	20.6%	44.1%	35.3%	100.0%
	Cramer's V = 0.380, p = 0.003			

[a] = frequency, [b] = row percentage

Figures

Figure 1. Separation-Concordance (SeCo) maps for the biomechanical outcome measures for both staircases for ascent and descent, highlighting the top 10% (of 500 initialisations of the k-means algorithm) with ΔSum of Squares (SSQ) on the y-axis and the internal median Cramer's V on the x-axis for each value of k (2-10). (A: *shallow* staircase ascent; B: *shallow* staircase descent; C: *steep* staircase ascent; D: *steep* staircase descent).